AIAA SciTech Forum 2023, National Harbor, Maryland, Jan 23–27, 2023

Progress of CFM Model Development and Validation at NASA Glenn Research Center

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Cryogenic Modeling Overview

- Brief Overview of Cryogenic Events
- Self Pressurization and Mixing for Pressure Control
- Helium and Autogenous Pressurization
- Propellant Transfer and Hardware Chill-down
- Sloshing with Phase Change
- Liquefaction for ISRU applications.
- Review

Acknowledgements

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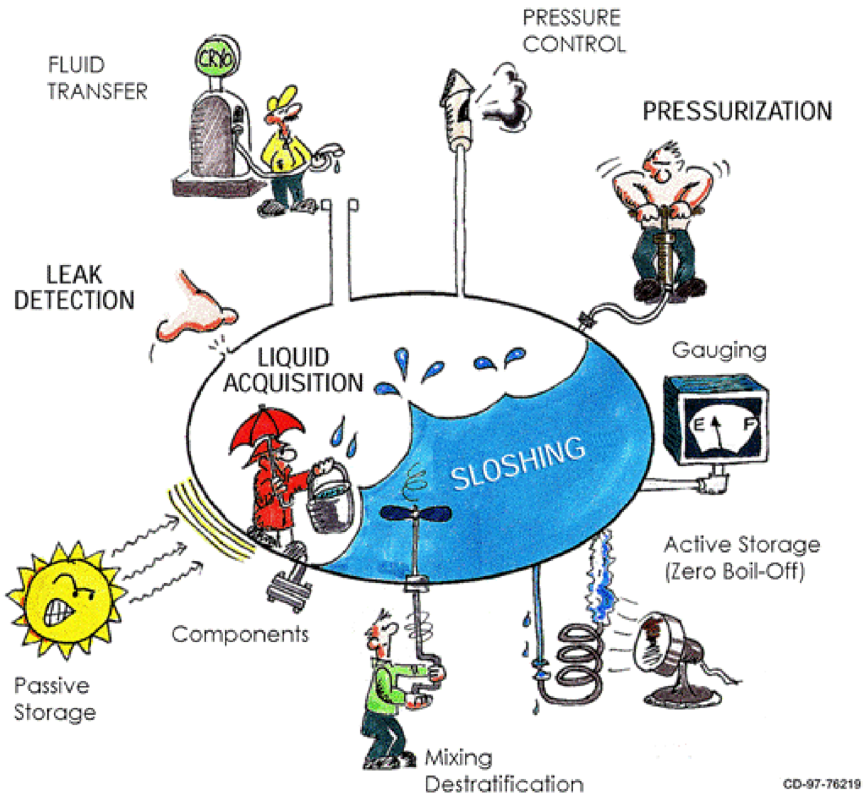
Cryogenic Predictive Model Development and Validation

- NASA has spent the past 20 years developing and validating multi-node and CFD modeling tools for cryogenic propellant applications.
- Past CFD model development efforts at NASA have resulted with validated and anchored models that are capable of predicting the conditions within propellant tanks and hardware with reasonable confidence.
- System level multi-node models as well as CFD models of these events have been developed and validated for the following cryogenic events.
  - Self-pressurization and pressure control-via axial jet and spray bar
  - Propellant transfer and chill-down of hardware including tanks, lines, and pumps.
  - Autogenous and helium pressurization of propellant tanks.
  - Sloshing with two-phase heat/mass transfer.
  - Liquefaction for ISRU operations including condensation of warm vapor within a propellant tank.
- NASA is working with industry, academia, and international partners to further improve these capabilities.

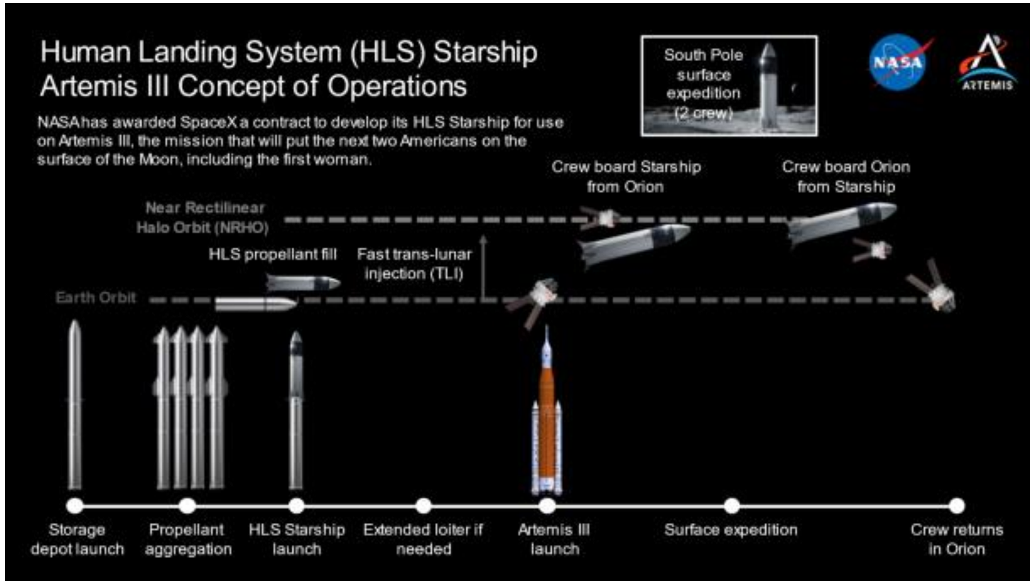


Cartoon Credit: J. Jurns

CFM Predictive Modeling Purpose

- In past and current public and private studies that utilize the long term on-orbit storage and transfer of cryogenic propellant, several mission events required the use of CFD models to better predict the performance of the hardware and operations within the architecture.
- One of our goals of is to adopt the lessons learned and apply them to NASA missions.
  - For example, these CFD tools and skills developed at MSFC and GRC are being used outside of the STMD CFM portfolio to support tipping points and Artemis mission applications.
- These Mission Events that members of the NASA modeling community are providing direct inline design support and independent V&V to reduce mission risk include:
  - **Pressurization**-Important for sizing equipment and operations for Autogenous and GHe pressurization systems (Impact: 10 mTon's of Propellant)
  - **Self-Pressurization**- Important for predicting the boil-off in propellant tanks in various mission locations(Lunar surface, Gateway, LEO for Depot applications).
    (Impact: mTons of Propellant)
  - **Sloshing**- Important for predicting how much residual pressurant is available during and after sloshing operations. (Impact: mTons of Propellant)
  - **Propellant Transfer** (Receiver tank chill-down and fill operations, donor Tank Pressurization and vapor pull-through)- Important for predicting the operations and hardware used in the transfer. (Impact: 10's mTons of Propellant)
- With more confident models these CFM systems could be designed with reduced margin and greater performance.

NASA HLS Starship Artemis III Concept of Operations

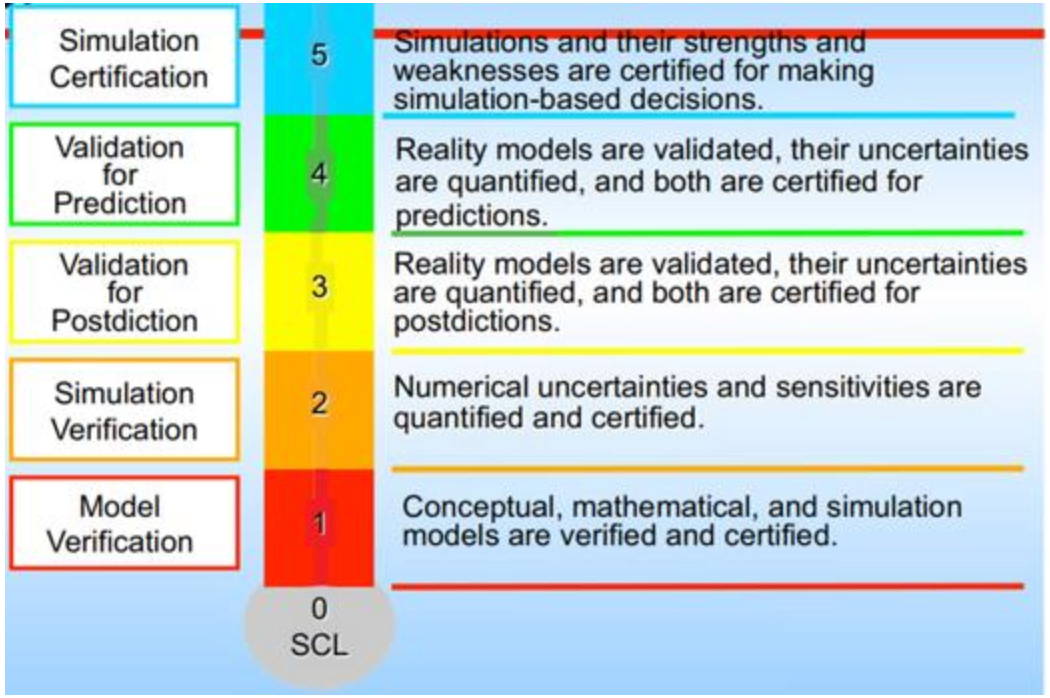


*Source: Watson-Morgan, U.B. (2022). "NASA's Initial Artemis Human Landing System" 73rd International Astronautical Congress(IAC) 18-22 September 2022, Paris, France,

Model Development and Validation

- NASA has a modeling and simulation standard (NASA STD 7009) that standardizes the reporting of a flight model credibility to managers when critical decisions are made.
- The standard was created as a result of the Columbia Space Shuttle Accident where seven astronauts lost their lives.
  - The Columbia Accident Investigation Board (CAIB) recommended a modeling and simulation standard to better communicate the credibility and of the model results/predictions.
- NASA STD 7009 is currently required for the HLS and Artemis program.
- Uses a Simulation Credibility Scale (SCL) that is based on several factors:
  - Are the M&S practitioners/analysts trained properly?
  - Is the model anchored against experimental data and does it agree?
  - Is the uncertainty of the results understood including sensitivity to parameters?
  - Has the model been used before for critical decisions?
  - Is the input data valid?
- Credibility Assessment Scale
  - Assesses the rigor of the processes used to produce the simulation results and determine their favorability against key factors that affect the credibility judgement.
  - Requires extensive documentation.
- STMD CFM modeling project focuses on ensuring the developed models capture the correct two-phase physics as well as increasing the Simulation Credibility Level of the models with anchoring the models to available experiments.
  - Also ensures personnel are properly trained.

NASA STD 7009
Simulation Credibility Level (SCL)

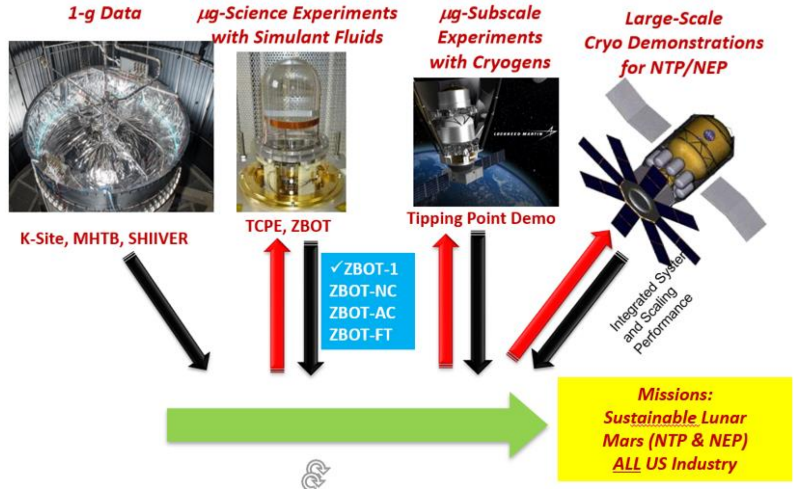


Source: Mehta, U.B. (2007). "Simulation Credibility Level." The 5th Joint Army-Navy-NASA-Air Force (JANNAF) Modeling and Simulation Subcommittee Meeting, CDJSC 49, May, CPIAC. Columbia, MD: Johns Hopkins University

CFM Modeling Overview

- More work is needed to close gaps in predicting the performance of cryogenic propellant in a low-gravity environment.
  - In low-g, capillary forces dominate body forces leading to non-intuitive and un-expected physics.
  - Better understanding and accurate models are critical for sizing hardware and operations for storage and transfer of cryogenic propellant in a low-gravity environment.
- Predictive Model Development work Includes:
  - First Principal Physics CFD model
  - Empirical based multi-node lumped models
- Models that are developed need to be anchored to experimental data in a relevant environment (large scale cryogenic propellant in a μ-g environment)

Infusion of Tipping Point Demonstrations to Anchor Cryogenic Models



Operation	Important Process/Mechanism	0G Sim Fluid Scaled	0G Cryo Small – Scale	0G Cryo Large - Scale
Self -Pressurization	Evaporation/Condensation	ZBOT-1	RRM3, TP	Future Demo
	Boiling - Nucleation	ZBOT-1		Future Demo
Pressure Control	Axial Jet Mixing	ZBOT-1 TPCE	TP	Future Demo
	Droplet Spray-bar	ZBOT-AC	TP	Future Demo
	Broad Area Cooling	ZBOT-AC	TP	Future Demo
Autogenous & He Pressurization Withdrawal	Unsubmerged		TP	Future Demo
	Submerged	CPST EDU	TP	Future Demo
Tank Chill-down & Filling	Inject-Hold-Vent Cycles		TP	Future Demo
Transfer line	Chill-down	ZBOT-FT	TP	Future Demo
	Heating/Boiling during steady state transfer	FBCE		Future Demo
Non-Condensable Effects	Pressurization	ZBOT-NC	TP	Future Demo
	Axial Jet Condensation	ZBOT-NC	TP	Future Demo
	Droplet Phase Change	ZBOT-AC	TP	Future Demo
Slosh	Like Pressurant		TP	Future Demo
	With Non-Condensable		TP	Future Demo
Liquefaction	Partial–g hot vapor condensation			Future Demo
	Transient Behavior			Future Demo

LEGEND

Current Modeling Understanding, Theory, Implementation:

- Complete understanding (green)
- Sufficient Eng. know how (yellow)
- Difficulties to overcome (blue)
- Large knowledge gap (orange)

Predicting tank self-pressurization as well as micro-gravity techniques to control tank pressure

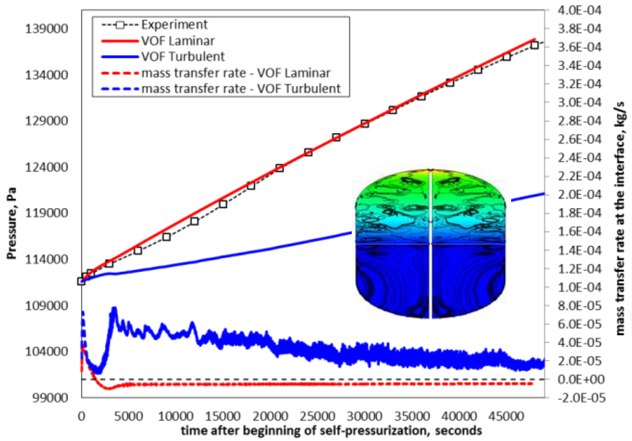
Cryogenic Tank Self-Pressurization and Pressure Control

- Cryogenic propellants are stored at very cold temperatures, due to the cold temperature, heat from the surrounding environment can cause the pressure in the tank to rise requiring venting propellant to release excess pressure or actively cooling the tank.
- Modeling these events present several challenges
  - Stratification or rising low density warm liquid to the surface occurs and causes the pressure to rise at higher rates than can be predicted by homogenous models.
  - Stratification in the tank can cause the pressure to rise quicker and suppress boiling.
  - Stratification in the ullage can significantly increase the temperature making it more challenging to estimate the pressurization rate.
- NASA has been developing and validating both CFD and multi-node thermo-fluid models to better predict this behavior.
  - CFD (FLUENT, FLOW-3D, STAR-CCM)
  - Multi-node (SINDA/FLUINT, GFSSP)
- NASA has validated several cryogenic self pressurization tests against experimental data in 1g and micro-g.
  - Ksite, MHTB, SHIIVeR (1g)
  - ZBOT, TPCE, RRM3 (micro-g)

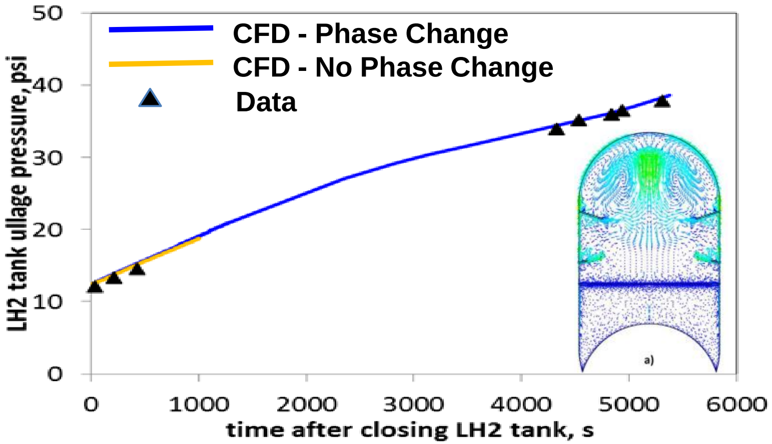
NASA has spent significant resources on developing and benchmarking both multi-node and CFD tools against experimental data.

Tank Self-Pressurization for Various Tank Sizes CFD Predictions versus Experimental

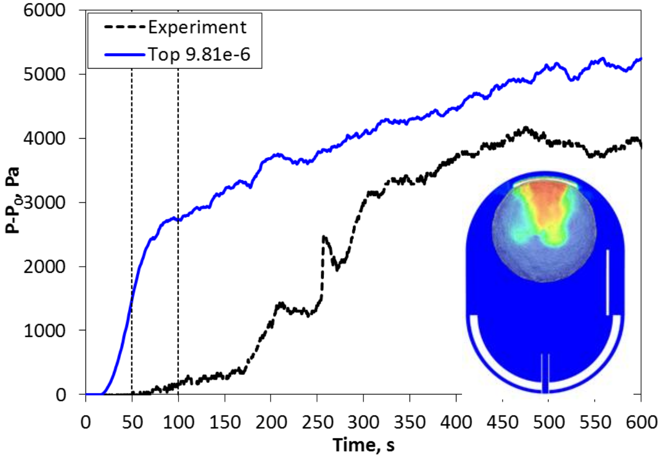
MHTB
1G
LH2
Large
1.5 W/m2



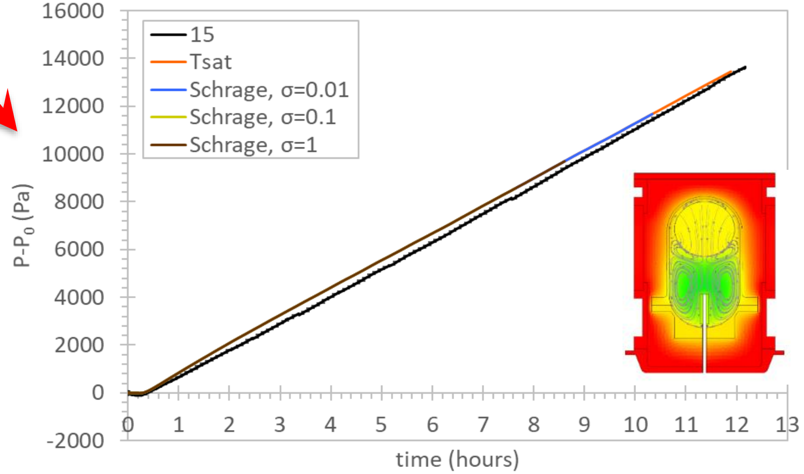
Saturn IVB
0G
LH2
V. Large
(Saturn AS203)
~30,000 W
~200W/m2



TCPE
0G
Freon
Small
(Shuttle)
16 W
900
W/m2



ZBOT
0g
PnP
Small
(ISS)
3-8
W/m2



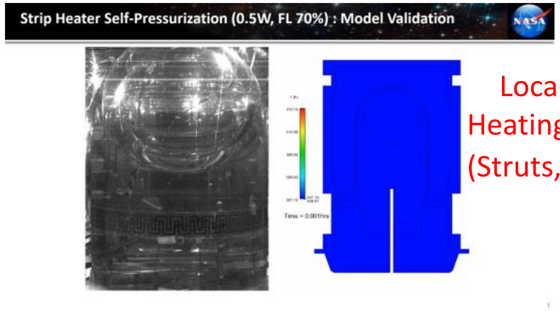
More work is needed to better predict pressure rise for large cryogenic tanks (>1.5m) where internal tank flow is turbulent.

ZBOT Experiment

Lessons Learned in ZBOT-1 to enable better CFM Predictive Modeling in μg

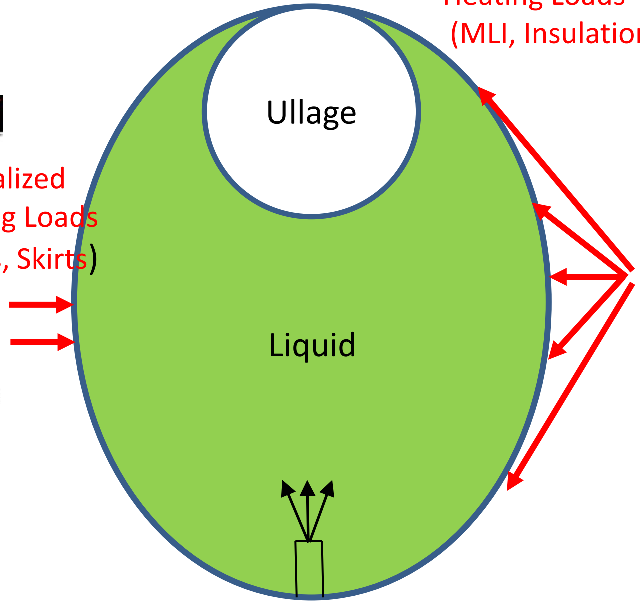
Pressurization(Localized Heating)

ZBOT Strip Heating



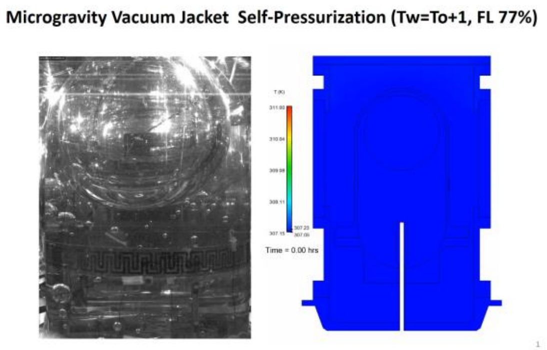
Distributed
Heating Loads
(MLI, Insulation)

Localized
Heating Loads
(Struts, Skirts)



Pressurization(Broad area Heating, MLI)

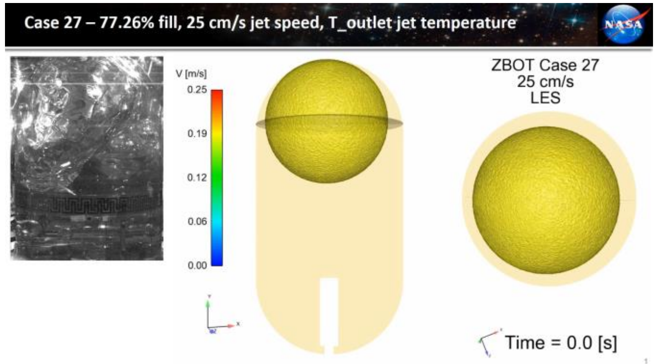
Vacuum Jacket Heating



Boiling on LAD's
During Mixing

Jet Mixing for
Tank Pressure Control

ZBOT Mixing Simulation: LES



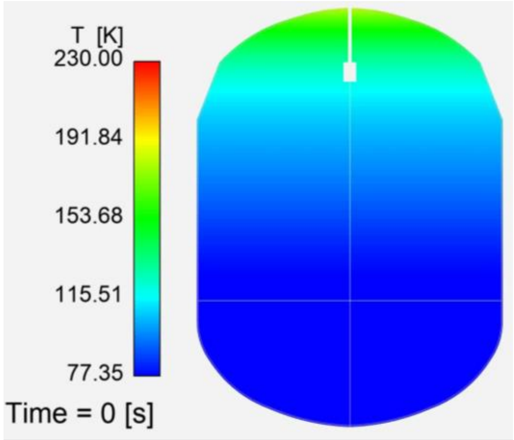
Strip Heater Boiling
(Self-Pressurization)

Predicting pressurization of a supply tank to be used for propellant transfer

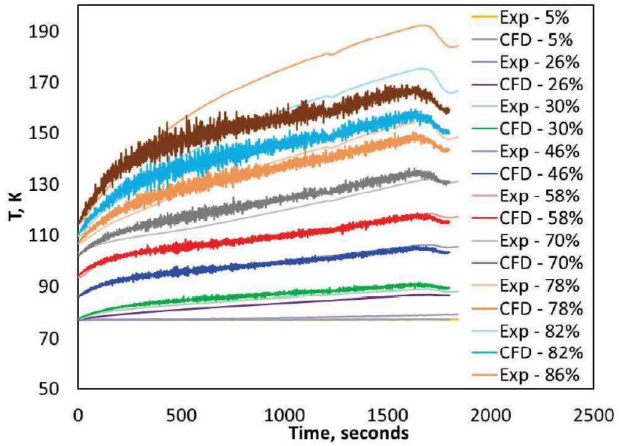
EDU Autogenous Pressurization Modeling (ANSYS FLUENT)

- Pressurization tests were conducted on ground test hardware in 2014/2015 to better understand the pressurization of a cryogenic tank using both an autogenous and helium pressurant.
- CFD models were created of the GN2/LN2 autogenous pressurization test using the commercial software ANSYS FLUENT.
  - User Subroutines developed previously were implemented to predict the two-phase liquid/vapor mass transfer that occurs at the interface.
- Models included both VOF and Sharp interface numerical schemes.
- Several CFD simulations were ran to investigate the following affects:
  - Grid/Mesh Independence
  - Laminar vs URANS turbulence model
  - Accommodation Coefficient (VOF)

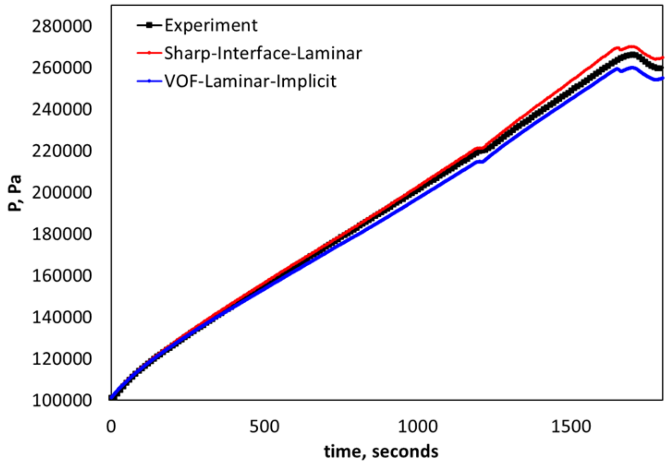
Predicted Temperature Contours of EDU GN2/LN2 Test



Predicted Vs Experimental Temperatures

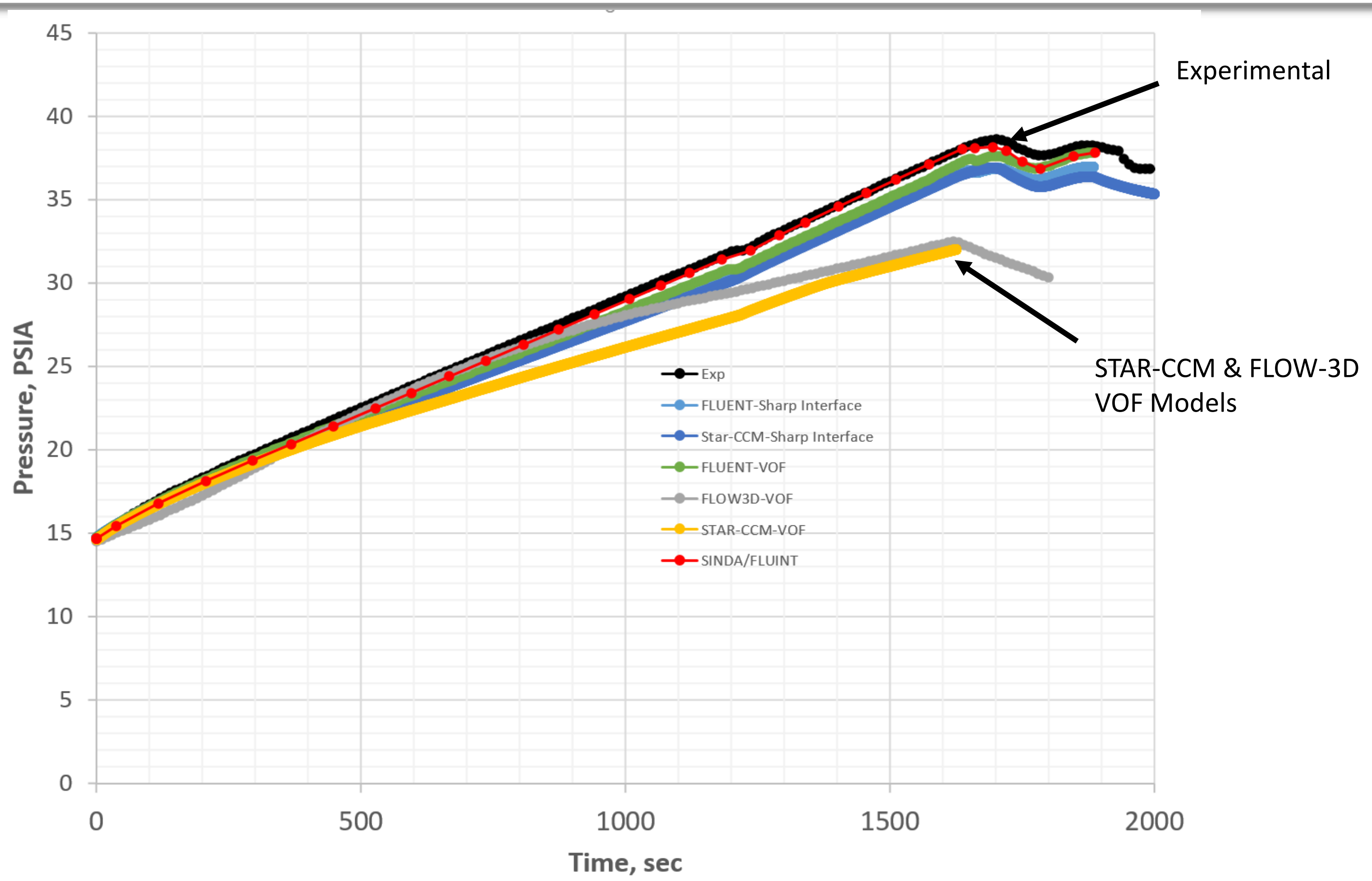


Predicted Vs Experimental Pressure



Both the FLUENT VOF and Sharp Interface CFD model predict the pressure in very good agreement with the experimental data. This indicates that FLUENT can confidently be used to predict the thermodynamic phenomena which occur when using autogenous pressurant to pressurize cryogenic tanks

EDU Predicted Pressure Signature Vs Experimental (All CFD and Nodal Predictions)

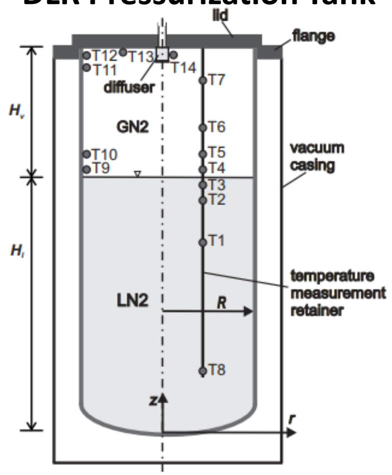


Both the FLUENT and STAR-CCM Sharp Interface CFD as well as the FLUENT VOF model predict the pressure in excellent agreement with the experimental data. This provides confidence in the commercial tools modified with NASA developed subroutines at predicting the thermodynamic phenomena which occur when using autogenous pressurant to pressurize cryogenic tanks (The FLOW3D and STAR CCM VOF model's both underpredict the pressure signature by 25% due to overprediction of ullage condensation.)

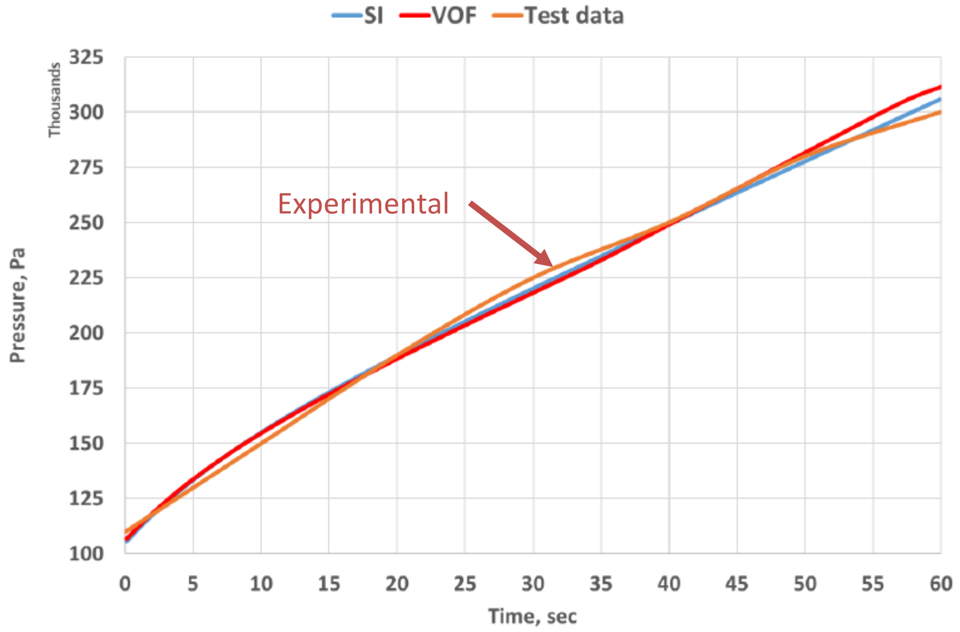
DLR Autogenous Pressurization Modeling (ANSYS FLUENT-Sharp Interface and VOF)

- An autogenous pressurization test was conducted by DLR/University of Bremen using GN2/LN2.
  - Published Paper on the test results in 2013.
- Similar to the EDU test tank, an autogenous pressurization model was built in the commercial software ANSYS FLUENT.

DLR Pressurization Tank



Predicted vs Experimental Pressure

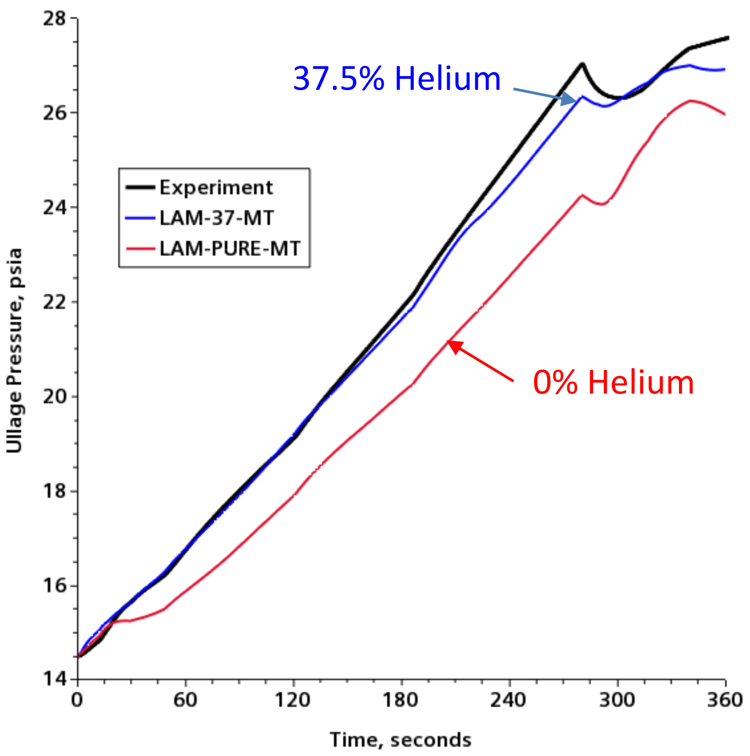


Both the FLUENT VOF and Sharp Interface CFD model predict the pressure in very good agreement with the experimental data. This indicates additional confidence that Fluent can confidently be used to predict the thermodynamic phenomena which occur when using autogenous pressurant to pressurize cryogenic tanks

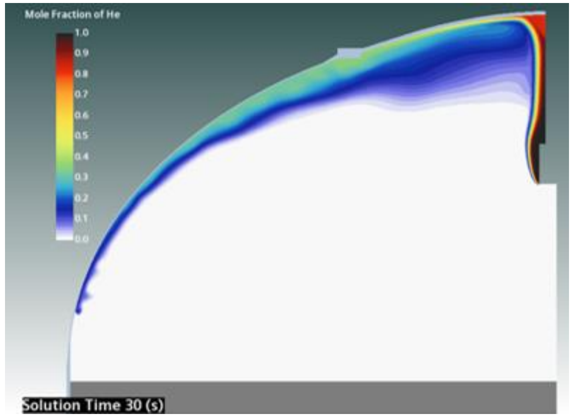
EDU Helium Pressurization Modeling (Star-CCM-Sharp Interface)

- A helium pressurization test of the CPST EDU tank filled with LH2 was modeled using the Sharp Interface approach that was implemented in Star-CCM.
- During the modeling, it was determined from test records that the tank did not initially contain pure GH2 due to an aborted helium pressurization test that contained residual helium, the tank was then vented to atmospheric pressure leaving a residual amount of helium in the ullage.
  - The pressure ratio's of the vent process were used to estimate an initial helium concentration of 37.5% by volume.

Predicted vs Experimental Pressure



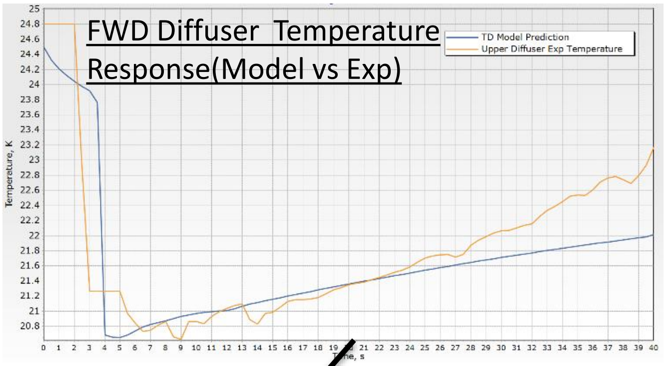
Predicted Helium Mole Fraction at 30 seconds (0% Initial Helium Case)

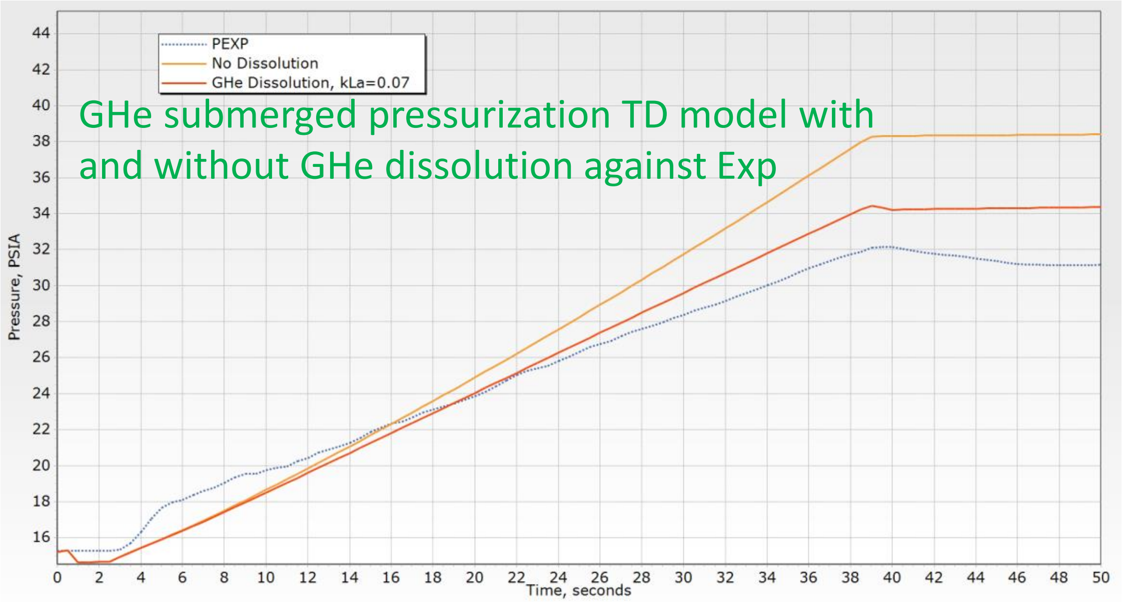


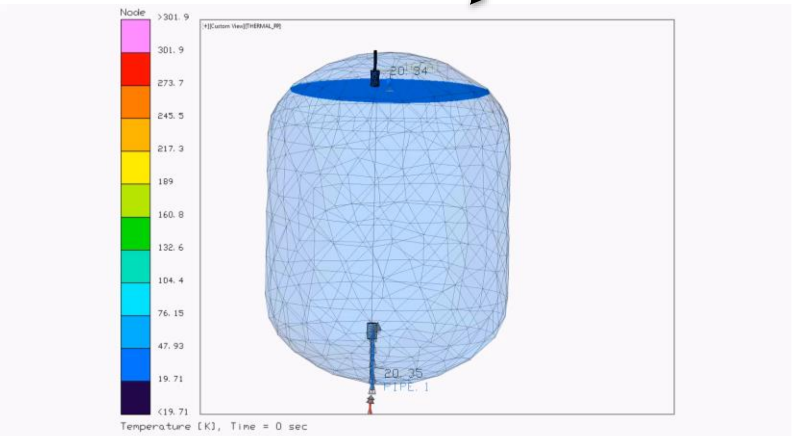
The sharp interface model implemented in Star-CCM gives confidence in the ability to predict the helium pressurization event well. The model shows that the initial helium concentration can drive additional evaporation at the interface. Additional development needs to be undertaken to capture the physics for a VOF formulation.

EDU Submerged Pressurization with GHe

- Due to the uncertainty of the ullage location in microgravity, submerged diffuser testing was conducted to determine the affect of the diffuser submerged in propellant.
- Submerged GHe pressurization modeled and validated using Thermal Desktop (SINDA/FLUINT).
- Tank wall and internal components modeled using a thermal FEA network.
- LH2 and GHe modeled as multi-node model with liquid, vapor, and interface modeled as separate lumps.
  - Empirical correlations used to predict heat transfer between liquid/vapor phases and conjugate heat transfer to wall and GHe dissolution into LH2.







Liquid Level during Submerged GHe Pressurization

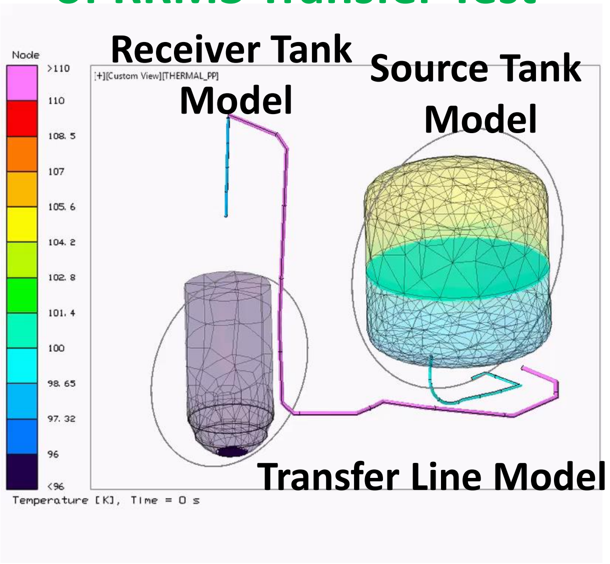
Multi-node analysis tool SINDA/FLUINT was extended to predict GHe dissolution rate into LH2 and validated against 1g experimental data for both a bang-bang and slow pressurization cycle.

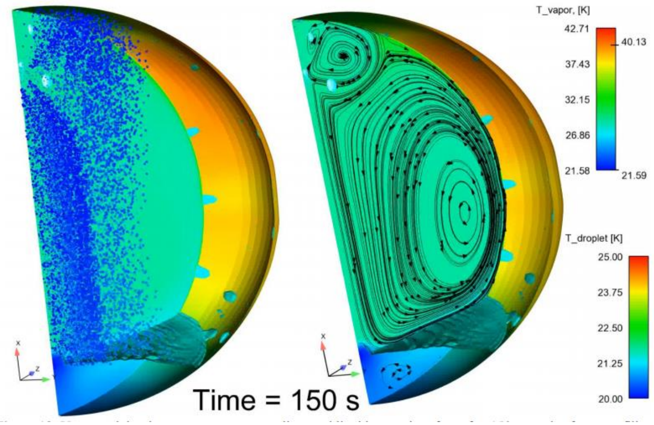
Predicting transfer operations including transfer line chill-down, tank chill-down and tank filling.

Propellant Transfer and Chill-down of Hardware

- Models of cryogenic propellant transfer and hardware chill-down have been developed and anchored to 1g experimental data using both multi-node and CFD predictive models.
- Modeling of propellant transfer process including chill-down of hardware (lines and tanks) using a quick multi-node approach is advantageous for multiple reasons:
  - Models can capture the multiple phenomena with reasonable fidelity that occurs during transfer including, pressurization with autogenous pressurant or GHe in supply tank, chill-down, propellant transfer, and collapse of receiver tank ullage pressure.
  - Two-phase cryogenic transfer process is highly dependent on thermal conditions in the hardware the cryogenic propellant contacts. Pressure in receiver tank is a direct function of the saturation temperature of the fluid.
  - Models can capture minimum supply tank pressures and maximum temperatures to ensure enough differential pressure between tanks is available to prevent lockup.
  - Can direct where higher fidelity (validated and anchored) predictive CFD tools could be applied.
- Higher fidelity CFD models of tank chill-down and propellant transfer operation have also been developed to more accurately capture the two-phase fluid and thermodynamics of the events that occur.
  - Spray droplet evaporation and spray boiling at the wall.
  - Natural convection after droplet evaporation both in 1g and reduced gravity environments.
  - Condensation within the ullage during the fill process.
  - Pressurization of the supply (source) tank as the tank drains propellant.

Thermal Desktop Model of RRM3 Transfer Test



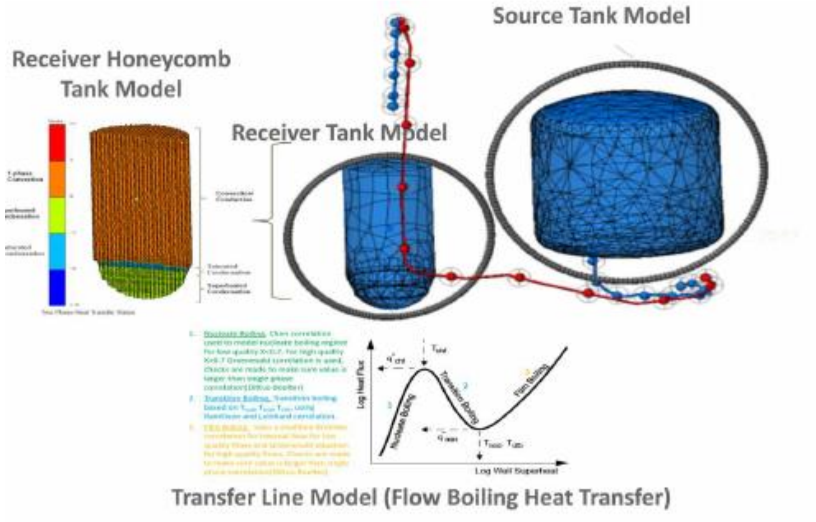


Ksite FLUENT CFD Vapor and Droplet Temperatures

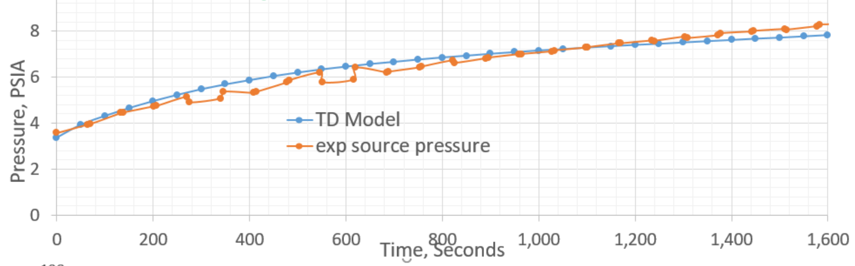
RRM3 Propellant Transfer Modeling

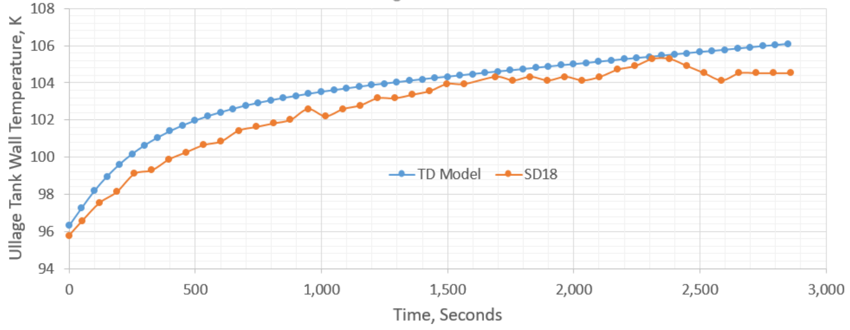
- A Thermal Desktop model was built to model tank thermodynamic, 2-phase fluid dynamics and heat transfer in both tanks and transfer lines for on-orbit performance with cryogenic methane.
- The Thermal Desktop model was updated to account for the environmental and operating conditions experienced during ground testing at KSC including natural convection.
- The model was used to predict transfer success prior to transfers and used to guide operating conditions within both the supply and receiver tanks.

RRM3 Thermal Desktop LCH_4 Transfer Model

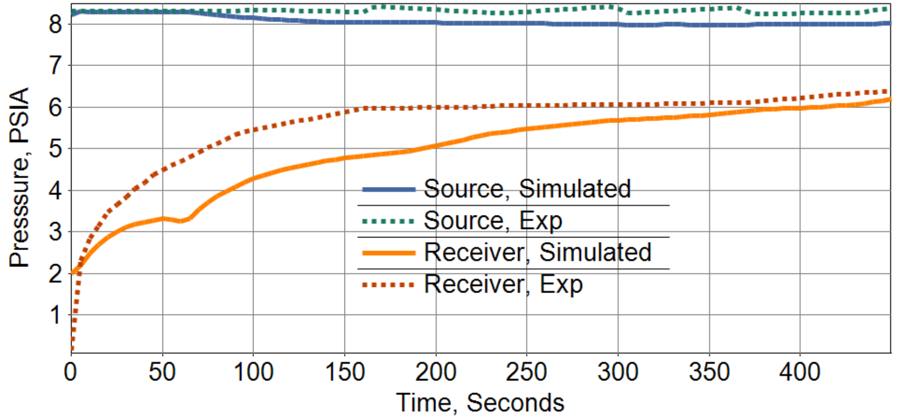


Predicted vs Exp Pressure and Temperature during Autogenous Pressurization





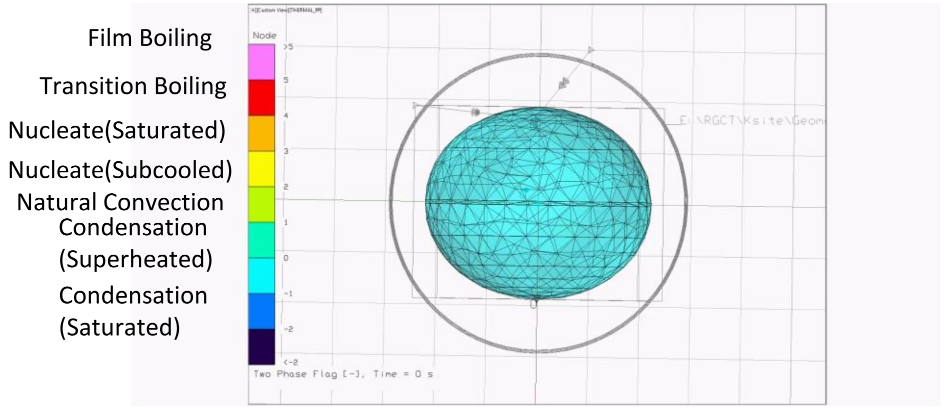
Predicted vs Exp Pressure During Successful Transfer



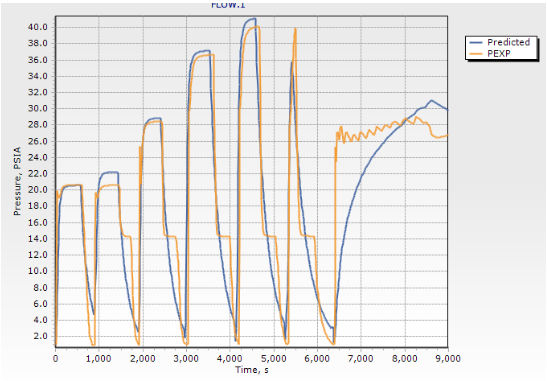
Ksite LH2-Tank Chill-down

- Thermal Desktop model of Ksite tank chill-down test with LH2 created in Thermal Desktop to model tank chill down and subsequent tank fill.
  - Tank chill-down was performed via a “charge-hold-vent” process until tank was chilled down to sufficient temperature.
  - LH2 was injected with spray nozzles at the bottom and top of tank.
- Previous modeling attempts of this event were performed with Eulerian-Lagrangian CFD analysis.
  - Model predicted pressure and temperature predictions were significantly different from experimental.
  - Poor results from CFD analysis were likely because of inaccurate flow rate measurements from turbine flow meter.
- Thermal Desktop analysis using a hybrid of measured flow rate and ideal gas assumptions to determine injected mass showed very good agreement with experimental pressure and temperature measurements.
  - Model accurately captures the various modes of heat transfer during the tank chill down and fill process with reasonable fidelity.
  - Model predicts the tank wall temperature during entire chill down and fill process with an average temperature discrepancy of 5 K.

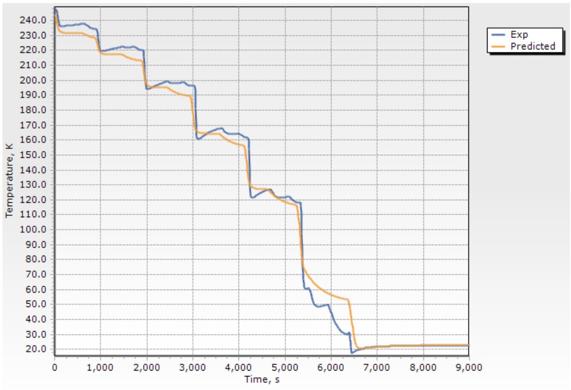
Heat Transfer Regimes During Tank Chill and Fill (TD Default)



Tank Pressure(exp vs Predicted)



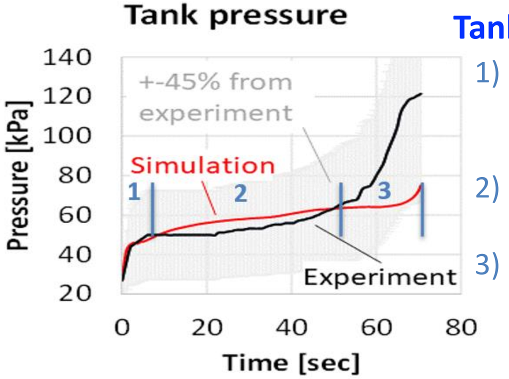
Tank Wall Temp(exp vs Predicted)



LH2 Tank No-Vent Chill and Fill Test

- A LH2 propellant tank chill and fill experiment was modeled using ANSYS FLUENT VOF with phase change included.
  - Significant gaps in documentation of several key geometric and operational parameters.
- The model predicted the three different tank filling regimes:
  - 1) Flashing and chill-down of tank 2) Ullage vapor condensation 3) Ullage Compression.
- The CFD model predicted the sudden (<2 sec) drop in tank wall temperature observed experimentally.
- The CFD model predicted the pressure rise up until the 90% fill level within 10% of the experimental pressure.
- The CFD model did not predict the sudden pressure rise that occurred after achieving a 90% fill level.
  - Possible presence of a non-condensable GHe left over from the tank purging process that affects the pressure rise during the compression process.

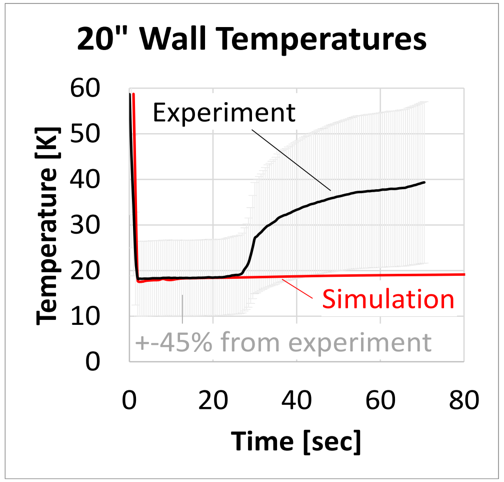
FLUENT Predicted vs Exp Pressure (Regimes 1-3)



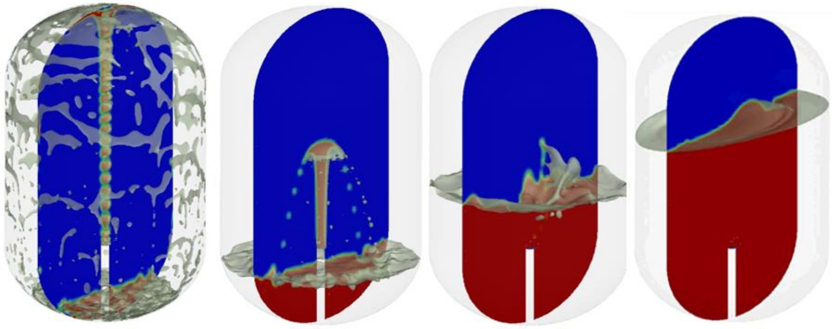
Tank Filling Regimes

1) Flashing at Inlet/Tank Chilling
2) Ullage Vapor Condensation
3) Ullage Compression

FLUENT Predicted vs Exp Top Wall Temperature



FLUENT Predicted Flow Regimes During Tank Chill and Fill

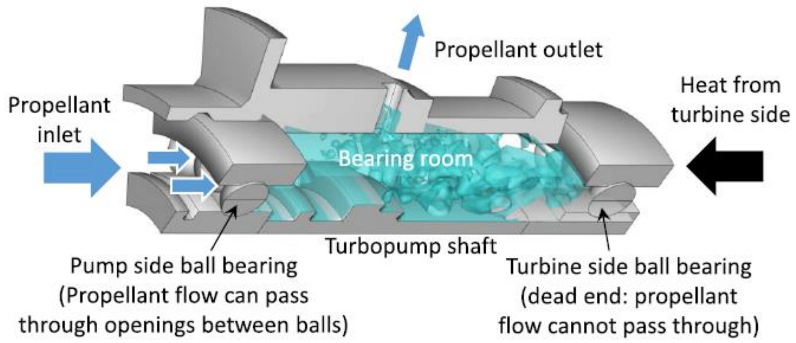


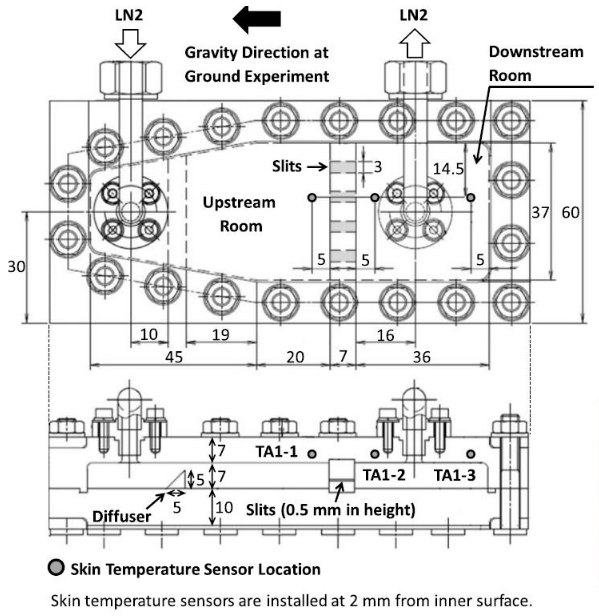
3 Seconds | 10 Seconds | 30 Seconds | 50 Seconds

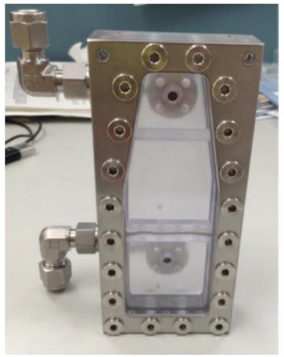
Despite the significant gaps in the documentation of key geometric and operational test parameters, the FLUENT VOF CFD model was still able to capture many of the behaviors involved with cryogenic tank chill and fill operations.

LN2 Turbo Pump Chill-down

- JAXA conducted ground and suborbital flight experiments to investigate chill-down of a test article representative of a cryogenic fluid turbopump bearing cavity in 1G and microG environments.
- LN2 injected at relatively low flow rates (0.5 & 1.0 g/s).
- Modeled experiments with multiple CFD numerical schemes using commercial code STAR-CCM.
  - Model predictions for surface wetting profile and temperatures matched experimental data for both 1g and micro-g.

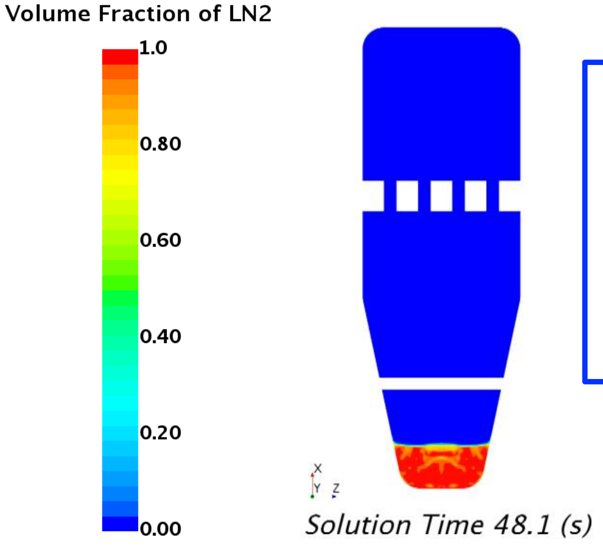




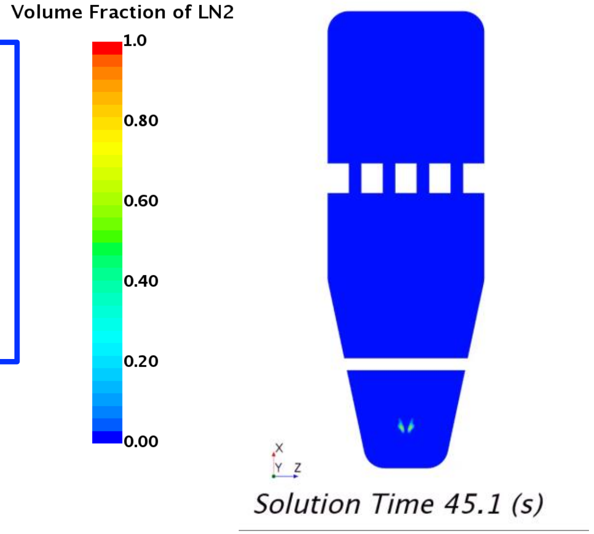


Flow Evolution 1G vs micro-g (Predicted vs Experimental)

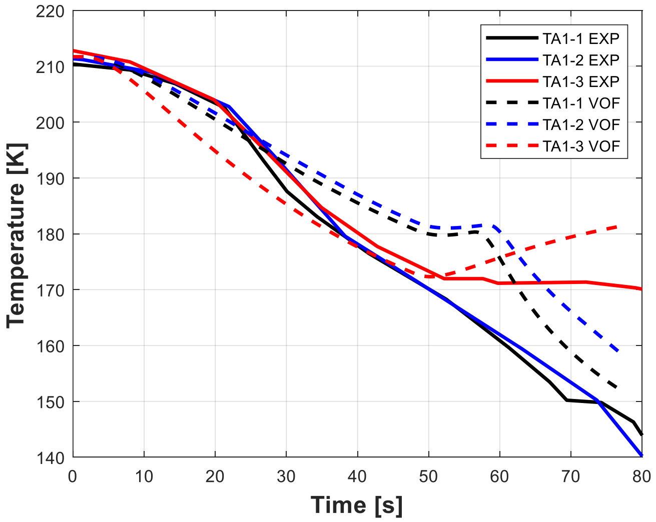
1-g

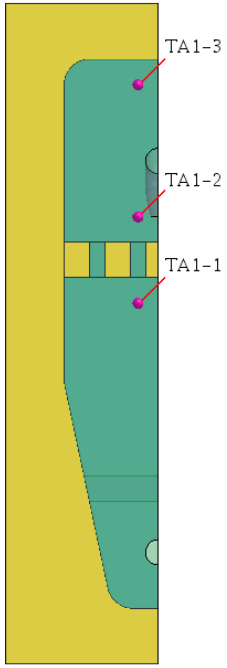


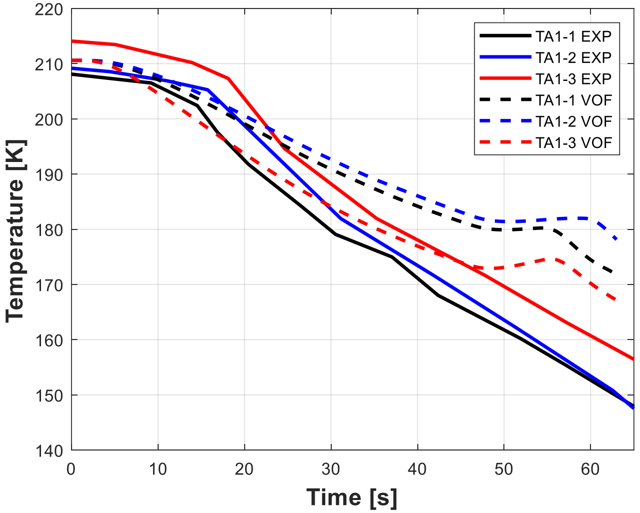
micro-g



Model predicts surface wetting of the back chamber which occurred in the experiment in the micro-g test





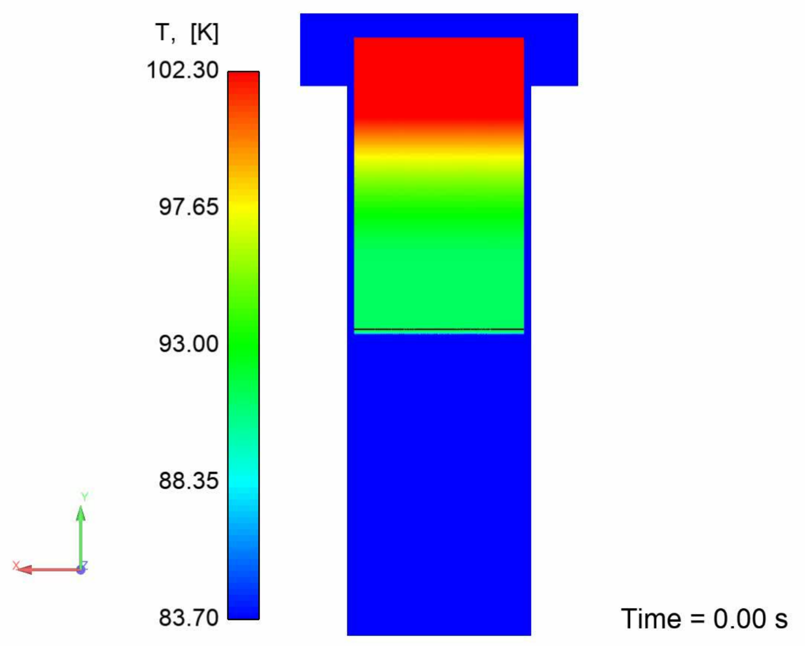


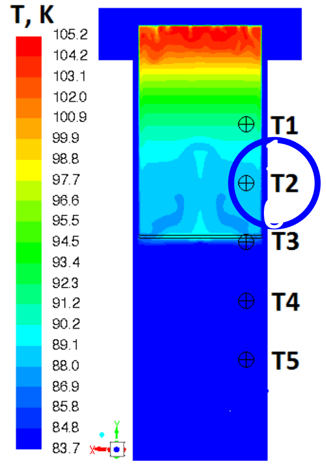
Predicting ullage collapse in a cryogenic tank (slosh)

Cryogenic Sloshing with Phase Change

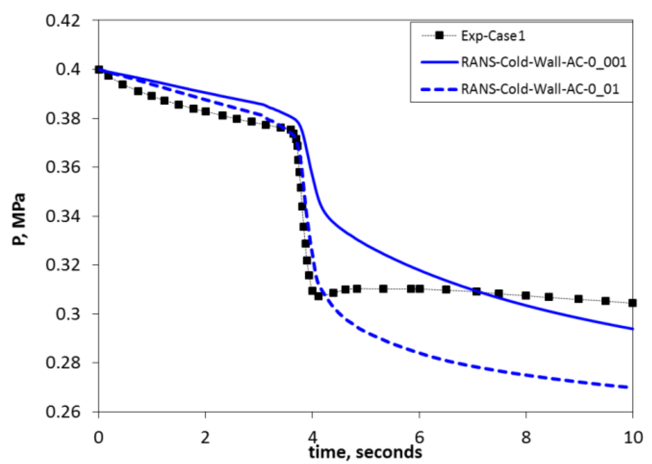
- **Validation of multiple cryogenic slosh CFD models using a VOF numerical framework within ANSYS FLUENT.**
  - Sloshing models include heat/mass transfer within the liquid/vapor.
- **Experimental data obtained through international partnerships with CNES and JAXA.**

LN2 Cryogenic Slosh CFD Simulation

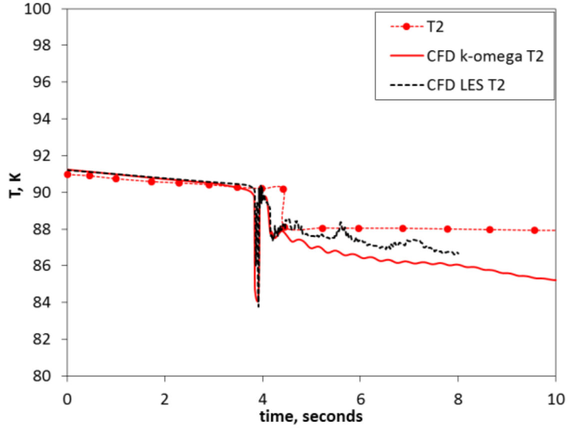




Pressure (Predicted vs Exp)



Temperature (Predicted vs Exp)



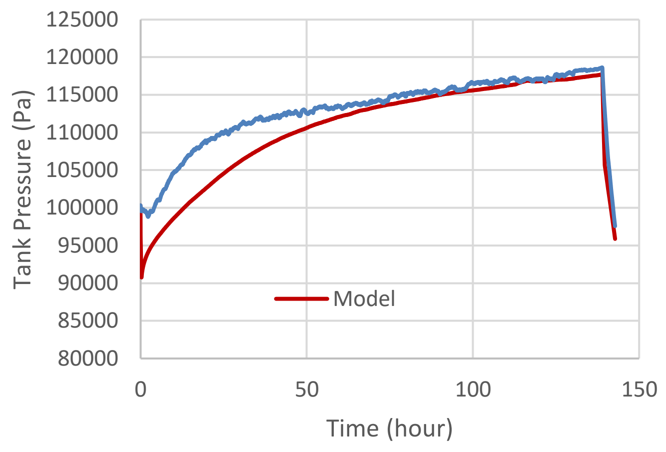
NASA has validated multiple cryogenic sloshing models with 2 phase heat/mass transfer.

Predicting the condensation within a propellant tank for In-situ-resource application

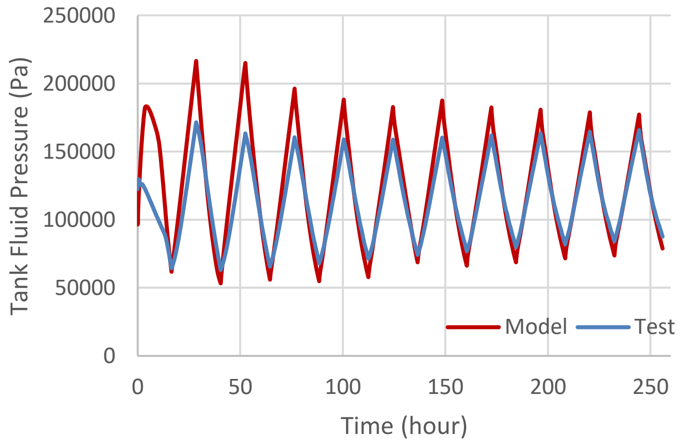
Liquefaction for ISRU Applications

- Liquefaction of cryogenic propellant was modeled within Thermal Desktop (SINDA/FLUINT).
  - Model included Neon Broad Area Cooling(BAC) loop.
  - Liquid/vapor propellant inside tank modeled as three lumps.
- Model was validated against experimental data from Brassboard testing where warm GN2 was introduced into tank.
  - Constant liquefaction
  - Non-Constant liquefaction
- Model predicts temperature and pressure within tank with reasonable fidelity.
- CFD modeling of liquefaction phenomena is currently being pursued to capture this phenomena with better fidelity.
  - Includes subgrid film condensation layer at wall coupled with a VOF model of bulk liquid/ullage.

Predicted Pressure vs Exp: Constant Liquefaction



Predicted Pressure vs Exp: Non-constant Liquefaction



Identified Gaps & Modeling Challenges

- Predicting the effects of non-condensable gases such as Helium pressurant on condensation within a propellant tank.
  - Important for tank pressurization, pressure control, tank fill operations and liquefaction operations.

- Predicting the performance of GHe pressurization *using* a diffuser submerged in cryogenic propellant in a propellant tank.

- Predicting the chill-down of transfer lines & engine feedlines using a 3D Navier Stokes CFD code coupled with a sub-grid boiling model.
  - NASA is currently funding an SBIR with CRAFT-TECH and MIT to extend a sub-grid boiling model developed for the Nuclear industry to cryogenic propellants.

- Predicting secondary bubble initiation and growth within a propellant tank due to vapor bubble initiation (boiling) caused by hot spots.
  - Two recent microgravity experiments (ZBOT and RRM3) saw evidence of the ullage/bubble relocating to regions of high heat flux.

- Predicting turbulence at the liquid/vapor Interface and its affect on two-phase heat/mass transfer.

- Predicting condensation within a propellant tank.
  - This has implications for liquefaction for ISRU operations but can also be important for tank filling in micro-g.

Conclusions

- In the past two decades NASA has made good progress on developing and anchoring both CFD and multi-node predictive tools related to CFM events.
- In the past ten years with the help of microgravity data from NASA and international partners, NASA has extended and anchored these tools to predict the performance in reduced gravity environments.
- Several gaps still exist within the current predictive models to predict the phenomena within two phase cryogenic systems with a high degree of confidence.
- These gaps present challenges that need to be addressed by developing capability within the CFD and multi-node codes to predict performance and by performing tests in microgravity to anchor and validate such models.

Acknowledgement

- Funding and programmatic support from the NASA Space Technology Mission Directorate (STMD)/ led by the Cryogenic Portfolio Project through the CFM Modeling Project as well as the Microgravity Biological and Physical Sciences (BPS) Division at NASA Headquarters through the ZBOT Experiment science investigations, funding of the Ksite analysis was provided through the Reduced Gravity Cryogenic Transfer Project within the STMD Cryogenic Portfolio Project.

CFM Modeling Status (Commercial CFD Tools)

Propellant Storage

MODEL V&V
Understanding, Theory, & Implementation: (NASA 7009 V&V)

- Well Understood (Level 3)
- Sufficient Eng. know how (Level 2)
- Difficulties to overcome (Level 1)
- Large knowledge gap (Level 0)

Data Pedigree of Benchmark Tests: (NASA 7009 Data Pedigree)

- Level 3 Test Anchored
- Level 2 Test Anchored
- Level 1 Test Anchored
- Future V&V Target
- No V&V target

Operation	Important Process/Mechanism	Numerical Implementation 1g (Settled)	Numerical Implementation 0g (Unsettled)	1G Sim Fluid Scaled	0G Sim Fluid Scaled	1G Cryo	0G Cryo Small –Scale	0G Cryo Large-Scale
Self-Pressurization	Evaporation/Condensation	☑	☑	ZBOT-1	ZBOT-1	K-site MHTB SHIIVER	RRM3	Future Demo
	Boiling	☑	☑		ZBOT-1		?	Future Demo
Pressure Control	Axial Jet Mixing	☑	☑	ZBOT-1	ZBOT-1 TPCE	K-Site	TP's	Future Demo
	Droplet Spray-bar	☑	Wall film formation	ZBOT-DP	ZBOT-DP	MHTB	TP's	Future Demo
	Broad Area Cooling	☑	☑	ZBOT-DP	ZBOT-DP	LOX ZBO	RRM3 TP's	Future Demo
Non-Condensable Effects	Pressurization	☑	☑	ZBOT-NC	ZBOT-NC	*Olsen*	**TP's**	Future Demo
	Axial Jet Condensation	☑	☑	ZBOT-NC	ZBOT-NC	Bullard LH2	**TP's**	Future Demo
	Droplet Phase Change	☑	☑	ZBOT-DP	ZBOT-DP	MHTB	**TP's**	Future Demo
Slosh	Like Pressurant	☑	☑			DLR/JAXA	**TP's**	Future Demo
	Unlike Pressurant	☑	☑				**TP's**	Future Demo
Low-g Tank Vent Operations	boiling/evaporation	☑	☑			N/A		Saturn AS-203
Liquefaction	Partial–g hot vapor condensation	☑	Partial - G			CryoFILL		
	Transient Behavior	☑	Partial- G			CryoFILL		

CFM Modeling Status-Continued (Commercial CFD Tools)

MODEL V&V
Understanding, Theory, &
Implementation: (NASA 7009 V&V)

- Well Understood (Level 3)
- Sufficient Eng. know how (Level 2)
- Difficulties to overcome (Level 1)
- Large knowledge gap (Level 0)

Data Pedigree of Benchmark Tests:
(NASA 7009 Data Pedigree)

- Level 3 Test Anchored
- Level 2 Test Anchored
- Level 1 Test Anchored
- Future V&V Target
- No V&V target

Propellant Transfer

Operation	Important Process/Mechanism	Numerical Implementation 1g (Settled)	Numerical Implementation 0g (Unsettled)	1G Sim Fluid Scaled	0G Sim Fluid Scaled	1G Cryo	0G Cryo Small –Scale	0G Cryo Large-Scale
Autogenous Pressurization	Unsubmerged	☑	☑			EDU	TP's	TP
	Submerged	☑	☑			EDU	TP's	Future Demo
Tank Chill-down	Inject-Hold-Vent Cycles	☑	Droplet-liquid coalescence – wall effects	ZBOT FT Tank Filling(DLR)	ZBOT FT Tank Filling(DLR	K-site	TP's	Future Demo
Transfer Line Chill-Down	Chill-down	☑	☑	FBCE-Line Chill-down	FBCE-Line Chill-down	GRC-LH2	TP's	Future Demo
	Heating/Boiling during steady state transfer	☑	☑	FBCE	FBCE	GRC-LH2 Hendricks	TP's	Future Demo
Tank Filling	Ullage Condensation during Fill Operation	☑	☑	ZBOT FT Tank Filling(DLR	ZBOT FT Tank Filling(DLR	LH2/Moran	TP's	TP
Non-Condensable Effects	Pressurization	☑	☑	ZBOT-NC	ZBOT-NC	*Olsen*	**TP's**	TP
	Axial Jet Condensation During Filling	☑	☑	ZBOT-NC	ZBOT-NC	Bullard LH2	**TP's**	Future Demo
	Droplet Phase Change	☑	☑	ZBOT-DP	ZBOT-DP	MHTB	**TP's**	Future Demo
Slosh	Like Pressurant	☑	☑			DLR/JAXA	**TP's**	TP
	Unlike Pressurant	☑	☑				**TP's**	Future Demo
Donor Tank Vapor Pull Through	Low bond # tank drainage	☑	☑	Abdalla/ Berenyi	Abdalla/ Berenyi	N/A		TP's